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COMPTOMIZATION AND RADIATION SPECTRA OF X-RAY SOURCES. CALCULATION OF THE MONTE CARLO METHOD

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16. Abstract

The results of computations of the Comptomization of low frequency radiation in weakly relativistic plasma are presented. The influence of photoabsorption by iron ions on a hard X-ray spectrum is considered.

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COMPTOMIZATION AND RADIATION SPECTRA
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CALCULATION BY THE MONTE CARLO METHOD

L. A. Pozdnyakov, I. M. Sobol', R. A. Sonyayev

I. COMPTOMIZATION OF LOW FREQUENCY RADIATION /3*

The change in the frequency of photons in the case of scattering by hot electrons is one of the basic mechanisms for the formation of radiation from X-ray sources [1]. Let us consider a spherical cloud of plasma with the radius R with the optical thickness according to the Thompson scattering $\tau = \sigma_T N_e R$ and the temperature $kT_e = \theta m_0 c^2$. In the center of the cloud, there is a source of low frequency photons with a Planck spectrum and the temperature $kT_r \ll kT_e$. In the case of scattering by hot electrons, the low frequency photons increase their energy and fall into the hard region of the spectrum. The energy of the photons leaving the cloud depends on the number of tested scatterings and on the electron temperature.

Using the diffusion approximation in [2], it was shown numerically and analytically in [3] and [4] that in this problem for $kT_e \ll m_e c^2$ and $\tau \gg 1$ the spectrum of outgoing radiation must be a power spectrum $I_\nu \sim \nu^{-\alpha}$, in a wide region of energy $3kT_r \ll h\nu \ll kT_e$, where the spectral index

$$\alpha = -\frac{3}{2} + \sqrt{\frac{9}{4} + \beta}, \quad \beta = \frac{\pi^2}{3\theta\left(\tau + \frac{2}{3}\right)^2} \tag{1}$$

Simultaneously, the studies [5] and [6] used the Monte Carlo method and showed analytically the same thing for an optically thin, $\tau \lesssim 1$, and relativistic and semi-relativistic plasma. In this

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*) The numbers in the margin indicate pagination of original foreign text.

case

$$\alpha \approx -\frac{\lg \tau}{\lg(an^2)}, \qquad (2)$$

where a = 12 at $n \gg 1$ .. The case of a slightly relativistic plasma $kT_e \approx 50 \div 250$ keV has not been studied. This case may be described by a simple Companeyts equation (since relativistic corrections are important). Among the sources of X-ray radiation /4 there are many bright ones in the 50 - 300 keV range (particularly, the sources Cyg X-1, Cyg X-3 and NGC 4151). This article has investigated the process of comptomization in a slightly relativistic plasma. The computational method is discussed in [6].

We confined ourselves to three values of the electron temperature: kT_e = 50, 100 and 256 keV and two values for the temperature of the low frequency photons: kT_r = 0.5 keV and 1.5 keV. The case kT_r = 0.5 eV, apparently corresponds to the situation in the nuclei of the galaxy and quasars, where the source of low frequency photons is infrared, optical or ultraviolet radiation.

Figure 1 gives the results of calculations. The radiation intensity decreases in the low frequency region $h\nu \lesssim kT_r$, retaining the Rayleigh-Jeans inclination nature of the spectrum. This effect was observed previously in [7].

In every case, the spectrum of X-ray radiation was a power spectrum up to $h\nu \sim 3kT_e$, , and in the variation τ = 5 at kT_e = 100 keV (Fig. 1c) there was a tendency toward the formation of a Wien spectrum with the average temperature kT_e .

At τ = 3 and energies of kT_e = 50, 100, 256 keV, the spectral indices equaled, respectively: α = 0.65, 0.35, 0.1 (the latter variation was calculated by the authors previously, see [5]).

This clearly confirms the results of the diffusion theory: formula (1) gives the values α = 0.68, 0.37, 0.16. At the same time it may be readily established that at $I \gtrsim 2$ it greatly exceeds the value of α.

Under these conditions, we may assume the semi-empirical formula /5

$$\alpha = \frac{-\lg\tau + 2/(n+3)}{\lg(12n^2 + 25n)}, \tag{3}$$

which at n >> 1 changes into (2). Formula (3) describes all of the variations with $\tau \leqslant 1$, which we have calculated (here and previously), as well as the variations with τ = 3 and n $\geq$ 0.5.

In the case of accretion of matter on a neutron star without a strong magnetic field, part of the gravitational energy liberated is changed into black-body radiation, and part goes toward the formation of a hot rarified upper atmosphere -- the analogue of the solar corona. A similar situation arises in the boundary layer in the case of disk accretion on a neutron star.

We shall model this situation in Fig. 2, selecting kT_r = 1.5 keV and kT_0 = 100 and 256 keV. It may be seen that for small τ the tail of hard X-ray radiation is formed in the spectrum. It is possible that this mechanism is responsible for a burst of hard X-ray radiation observed on Sco X-1 (see the summary of the experimental data in [8]).

II. PHOTOABSORPTION AND COMPTOMIZATION

Let us consider a cloud of a comparatively cold plasma (kT_e = 0 or kT_e = 0.1 keV) with an optical scattering thickness τ. In the center of the cloud we assign the source of hard X-ray photons with a power spectrum $I_\nu \sim \nu^{-1}$. We are interested in a change of

the radiation spectrum due to the interaction of photons with electrons.

Since the change in the photon energy due to the recoil effect is greater than the ionization potential of a hydrogen atom, it does not matter whether scattering occurs for free electrons or for electrons connected in the hydrogen atoms. /6
We also consider photoabsorption by atoms and ions of slightly ionized iron. The problem is a model problem: We do not consider the degree of ionization (close to the X-ray source it may be very large). We assume that elements with $Z < 26$ are strongly ionized by X-ray radiation, and therefore there is insignificant photoabsorption of photons with $h\nu < 7$ keV. At $h\nu > 7$ keV, photoabsorption of the photons by an iron ion is accompanied by radiation with the probability of 0.34 of a photon K_α (with $h\nu_0 = 6.41$ keV). The cross section at photoabsorption threshold is assumed to equal σ_T. This corresponds to a decrease of the *) of iron by a factor of 2-3 as compared with the solar value or its photoionization.

Figures 3 and 4 give the results of the calculation. It may be seen in Fig. 3 that the difference in the plasma temperature is only observed on the profile of the K_α line. The role of the photoabsorption is so great that at $\tau > 1$ absorption boundary may be assumed to be a sharp drop in the spectrum (Fig. 4). If the photoabsorption cross section exceeds the Thompson cross section at the absorption boundary, then the effect will be more pronounced (this fact was noted in [9]).

The spectral resolution of the calculation in the vicinity of the K_α line equals 0.05 keV. The line produced has a colossal equivalent width W. For example, at $\tau = 1$ and $kT_e = 0$, we have

$$W = \int_{5.75}^{6.55} \left[I_\nu - I_\nu(0) \right] dh\nu \cdot \left[I_{\nu_0}(0) \right]^{-1} = 0.4 \text{ keV}$$

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*) Illegible in foreign text.

This is not surprising, because a third of the absorbed photons with $h\nu > 7$ keV overlaps the K_{α} line. The line intensity may decrease only when there is strong photoabsorption by the lighter elements.

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FIGURE CAPTIONS

Fig. 1. Spectrum of a central source with a temperature of $kT_0 = 0.5$ eV and the radiation spectrum emanating from a cloud for different kT_e and τ.

Fig. 2. Spectrum of the central source with a temperature of $kT_0 = 1.5$ eV and the radiation spectrum emanating from a cloud for different kT_e and τ.

Fig. 3. Evolution of continuous spectrum (direct) as the result of Compton scattering and photoabsorption at different temperatures kT_e of the cloud.

Fig. 4. Evolution of the continuous spectrum (direct) as the result of Compton scattering and photoabsorption for different thicknesses τ of the cloud.

/9

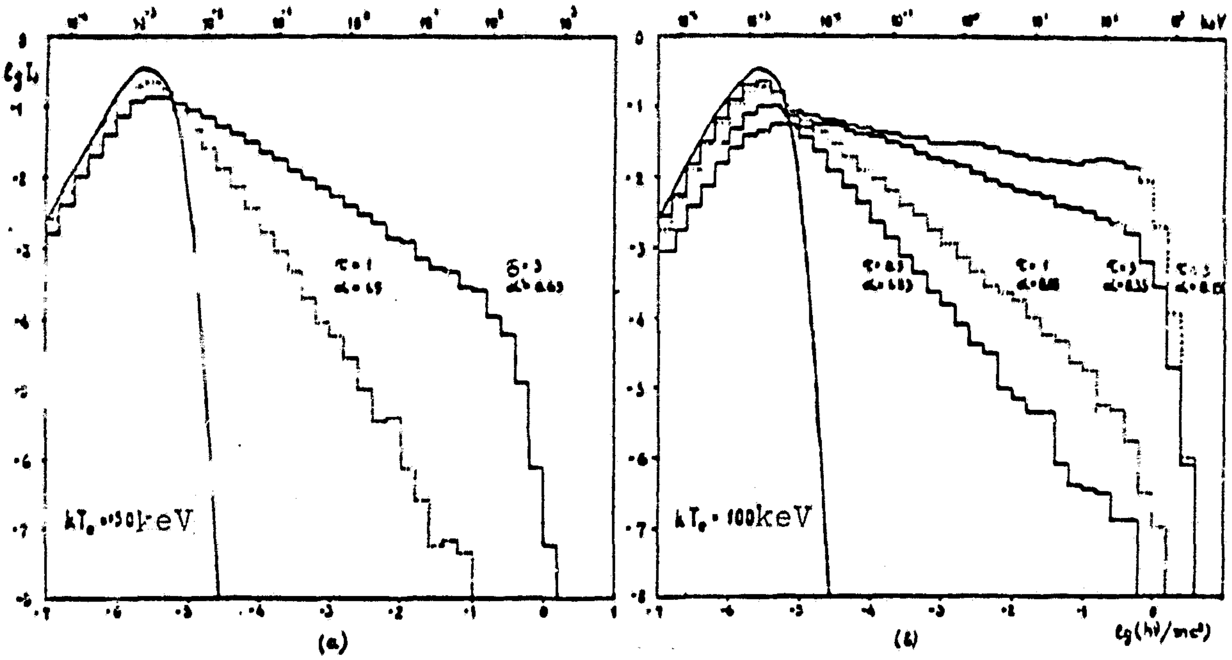


Fig. 1

/10

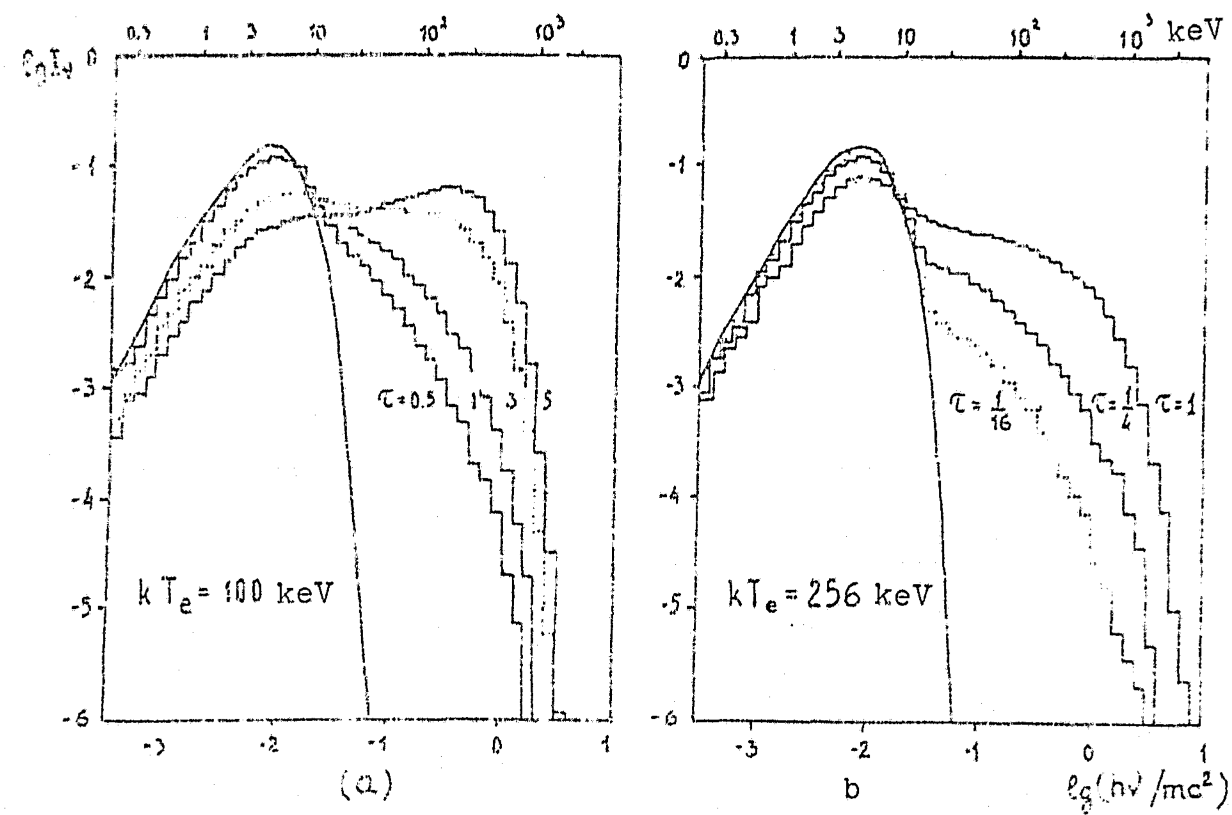
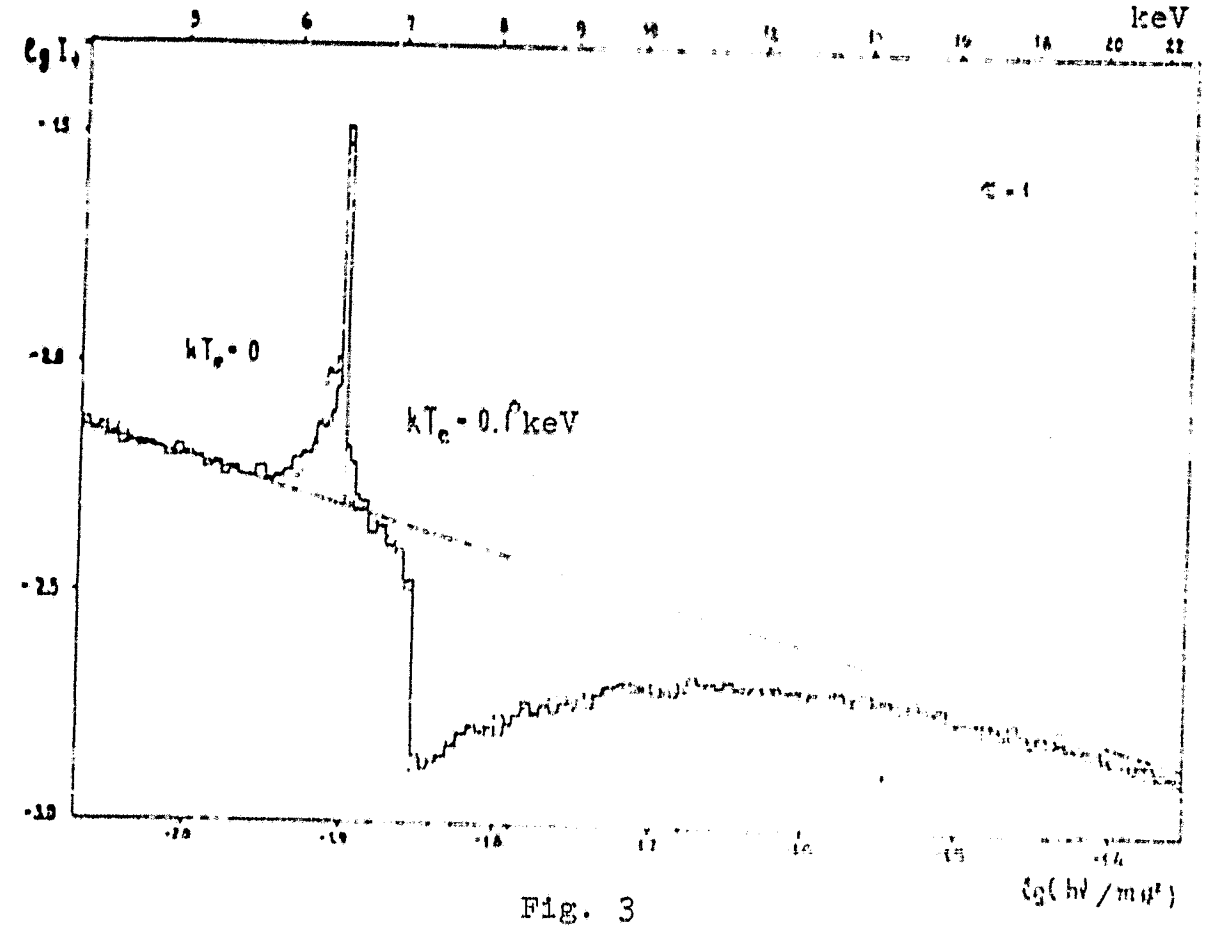
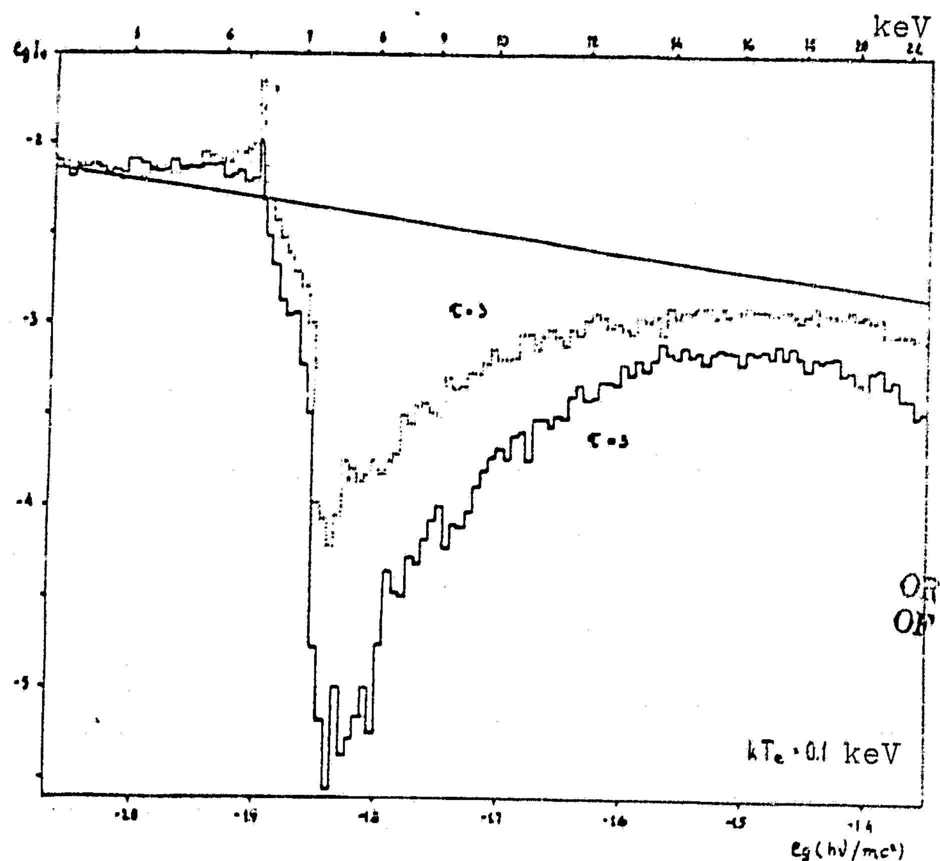


Fig. 2



/11

Fig. 3



/12

Fig. 4